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A novel two-body sensor system to study spontaneous movements in infants during caregiver physical contact

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ABSTRACT

Spontaneous movements, which refer to repetitive limb movements in the absence of any external stimulus, have been found to be reflective of neurodevelopmental status during infancy. These movements are modulated by both individual and environmental factors, including physical contact (holding) with the caregiver. However, it is a challenge to measure spontaneous movements during physical contact because infant-generated movements become coupled with caregiver-generated movements in such contexts. Here, we propose the use of a novel two-body sensor system to distinguish infant-generated movements in the presence of physical contact with the caregiver. Data from seven typically developing infants and their caregivers were recorded during different simulated home activities, which involved different combinations of physical interaction, caregiver's movement and infant positions. The two-body sensor system consisted of two wearable accelerometers – one placed on the infant's arm and one on the caregiver's arm, and we developed a Kalman-filter based algorithm to isolate the infant-generated movements. In addition, video was recorded for qualitative analysis. Results indicated that spontaneous movement activity was higher when there was no physical contact with caregiver. When there was physical contact, spontaneous movements were increased when the caregiver was still and when the infant was held horizontally. These results show that the novel two-body sensor system and the associated algorithms were able to isolate infant-generated movements during physical contact with the caregiver. This approach holds promise for the automated long-term tracking of spontaneous movements in infants, which may provide critical insight into developmental disorders.

1. Introduction

Spontaneous movements observed during infancy play a critical role in early motor development (Kravitz & Boehm, 1971; Piek & Carman, 1994; Prechtl & Hopkins, 1986; Wolff, 1968). These movement patterns, such as leg kicking and arm waving, are observed in typically developing infants throughout the day in absence of any apparent external stimulus. Despite looking random, these movement patterns carry both functional and clinical significance in the growth and maturation of neuromuscular system. Functionally, they play an important role in the development of coordinated and complex motor control (Thelen, 1981). For instance, spontaneous movements such as arm banging and waving movements are precursors to reaching skill acquisition (Thelen, 1981). Clinically, these movements are predictive of neurological disorders during early infancy (Prechtl, 1989). For instance, the General

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Movement Assessment (GMA; Prechtl, 1990) used for detecting cerebral palsy in neonates is based on the qualitative analysis of spontaneous movements. Thus, understanding spontaneous movements and their characteristics during early infancy remains an important issue in motor development.

Different individual and environmental factors influence the characteristics of spontaneous movements. For example, when considering individual factors, Prechtl and colleagues found age-related changes in characteristics of spontaneous movements with an increase in frequency prior to the onset of goal directed movements (1997, Prechtl, 2001; Prechtl, 1990; Prechtl & Einspieler, 1997; Prechtl, Ferrari, & Cioni, 1993; Prechtl & Hopkins, 1986). Similarly environmental factors such as the presence of a toy have also shown to influence the speed and number of these movements (Bhat & Galloway, 2006; Bhat, Heathcock, & Galloway, 2005). As a result, it is important to account for the effects of various environmental and individual factors on spontaneous movements while studying their functional and clinical significance during early infancy.

One important environmental factor is the interaction of infants with their caregiver, especially through physical contact. In this context, physical contact refers to the contact between the infant and the caregiver when the infant is being held and raised off the ground (Lamb, 1977). This interaction where the caregiver holds their infants to soothe them is not only frequently observed during early infancy (Bell & Ainsworth, 1972; Wolff, 1969) but is also critical for the overall development of infants. Starting from the seminal study of Harry Harlow (Harlow, 1959), the importance of caregiver physical contact in social and cognitive development of infants has been well established (Anisfeld, Casper, Nozyce, & Cunningham, 1990; Reite, 1990). In addition, physical contact also shows effects on physical growth of infants as evident from the benefits of ‘kangaroo care’ that help to improve weight gain in preterm and low birth weight babies (World Health Organization, 2003). However, despite the significance of physical contact in multiple facets of infant development (Ainsworth, Blehar, Waters, & Wall, 2015; Bowlby, 1969; Esposito et al., 2013; Heller, 1997; Weiss, 1979), its effect on spontaneous movements is relatively poorly understood.

A key barrier to studying the effect of physical contact on spontaneous movements is that physical contact couples the movement of the caregiver and the infant, creating a measurement problem. Most studies of spontaneous movements only use sensors (either markers or accelerometers) on the infant to capture motion when the infant is lying on its back (Disselhorst-Klug, Heinze, Breitbach-Faller, Schmitz-Rode, & Rau, 2012; Karch et al., 2012; Meinecke et al., 2006; Smith, Trujillo-Priego, Lane, Finley, & Horak, 2015); however, when there is physical contact, the sensor data is affected both by movements from infant and caregiver, making it very difficult to distinguish between active movements made by the infant and passive movements of the infant induced by the caregiver. This issue is especially critical considering that ‘external motion’ (i.e. motion of the infant due to external sources such as a caregiver or equipment such as a bouncer) can account for up to 40% of activity time, with 75% of this time coming from caregiver motion (Tsai, Burr, & Thomas, 2009). Therefore there is a critical need to develop a way to disentangle the infant and caregiver movements when they are in physical contact.

To address this need, here we develop and test the use of a ‘two-body’ networked sensor system to measure infant spontaneous movements during physical contact. In this system, sensors are placed on both infant and caregiver in order to record their movements simultaneously. Using data from both sensors, it is feasible to (i) identify the time intervals in which infant is in physical contact with the caregiver, and (ii) during such periods of contact, use a signal separation method to ‘filter out’ the caregiver movements from the infant sensor data to provide an estimate of the infant-generated movements. This automated method of extracting infant movements could potentially reduce reliance on qualitative data (such as video data, dairies), and save manual time and energy required for coding behavioral video data.

A second factor that is important in considering the role of physical contact in spontaneous movement is the position of the infant. Caregivers hold infants in different positions for different purposes - for example, infants are held in a horizontal position during nursing but are held in a vertical position for burping and putting them to sleep. There is evidence that this change in position can influence spontaneous movements (Carvalho, Tudella, & Savelsbergh, 2007; Savelsbergh & van der Kamp, 1994). Savelsbergh and colleagues found that pre-reaching movements, a type of spontaneous movement behavior, increased when the infant was in the vertical position. Similarly, Soska and Adolph (2014) found an increase in reaching and mouthing activity when the infant was in supine position as compared to prone position. However, these studies assessed the effect of infant position in the absence of physical contact – therefore, how physical contact influences the relation between infant position and spontaneous movements is not known.

In this study, we investigate the role of physical contact and infant position on the characteristics of spontaneous movements using the two-body networked system during simulated activities that are commonly observed during infancy. To study the effect of physical contact, spontaneous movements were assessed under two conditions– caregiver holding the infant (hold condition) and caregiver not holding the infant (no hold condition). When the infant was held by the caregiver, we also examined the role of whether the caregiver was moving or still. To study the effect of infant position, spontaneous activity was assessed under four positions– vertical or horizontal (when baby is held by caregiver), and lying on the back or the tummy (when they are not held). We tested the hypothesis that (i) physical contact results in less spontaneous movement activity (Thelen, 1981), and (ii) there is increased spontaneous activity in vertical position compared to the horizontal position (Kawai, Savelsbergh, & Wimmers, 1999).

2. Method

2.1. Participants

Seven typically developing full term infants (5 males; *mean age for the sessions used for statistical analysis* = 14.47 weeks; *SD* = 4.82 weeks) participated with their primary caregivers (parents) in this study. Infants in this age group were recruited as the onset of spontaneous movements in arms range between 6–22 weeks (Thelen, 1979). Inclusion criteria for infants were (i) born at term age,

(ii) not diagnosed with developmental delay, and (iii) not identified as high risk for any developmental disorder (i.e., did not have a sibling with a diagnosis). The answers to these questions were self-reported by the parent or caregiver. The total number of lab visits varied among participants. Three infants were tested multiple times every 2 weeks (5, 3 and 3 times), while the other four infants were only tested once, making a total of 15 lab visits across the seven infants. The number of lab visits varied across the participants as subsequent lab visits were scheduled based on the caregiver's availability. Each lab visit was compensated with $10 cash. Caregivers provided written informed consent and procedures were approved by the Michigan State University human research protection program.

2.2. Apparatus

Movement data was recorded using two custom-made sensors, each for measuring infant and caregiver activity. The sensors were 3- axis accelerometers. Sensors were attached using adjustable armband with a Velcro strap for caregiver's arm and customized cloth sleeve with a pocket for infant's arm. Sensors were always attached with their X-axis along the long axis of body and on the right upper arm.

The justification for placing the sensor on the arm was based on the assumption that when holding the infant, the caregiver arm moves as a unit with the elbow and wrist joint acting as rigid joints. Moreover, infants at this age are found to have 'linear synergy' in the proximal to distal pattern of upper limb movements and mostly rely on inherent properties of arms to produce movements (Galloway & Thelen, 2000; Gottlieb, Song, Almeida, Hong, & Corcos, 1997; Zaal, Daigle, Gottlieb, & Thelen, 1999). Therefore sensor placement on the infant's upper arm instead of elbow or wrist ensured maximal capturing of their movements as well as secured positioning.

We also recorded video using a video camera. The camera was positioned to provide an aerial view of entire experimental setup in order to record all the caregiver and infant activities during the experiment. Prior to the start of data collection, the experimenter synchronized the video and sensor data by wearing the sensor and performing a distinct hand gesture (which could be measured both on the sensor and seen on the video).

2.3. Procedure

Spontaneous movements in infants were assessed for different combinations of physical contact, caregiver movement, and infant positions that are routinely observed in home environments. We examined spontaneous movements in a total of 6 conditions– (1) infant independently lying on their tummy (no hold), (2) infant independently lying on their back (no hold), (3) caregiver holding infant in vertical position and moving (like walking or rocking and bouncing infant) (hold + moving), (4) caregiver holding infant in horizontal position and moving (hold + moving) (5) caregiver holding infant vertically and remains still (hold + still) and (6) caregiver holding infant horizontally and remains still (hold + still) (Table 1).

During each lab visit, caregiver and infant were outfitted with sensors on their right arm (Fig. 1a) and video recorded while performing activities based on above mentioned conditions. Each lab visit consisted of two sessions, 20 min each. Each session consisted of 20 activities that belonged to one of the 6 conditions (6 activities in the hold + moving condition, 6 activities in the hold + still condition and 8 activities in the no-hold condition). There was a slightly larger number of activities recorded in the no-hold condition to ensure that we had sufficient trials to train the machine learning classifier to distinguish between the hold and no hold conditions. Each activity lasted for 1 min and was performed based on a randomly generated sequence during each session. Caregivers were cued about the transition to a new activity before the end of current one. Experimental sessions were stopped when infants started crying continuously or when the caregiver requested a break.

3. Data analysis

Data analysis consisted of qualitative analysis of the video data, and quantitative analysis of the sensor data.

Table 1
Six mutually exclusive conditions set as a combination of different combinations of physical contact, caregiver movement and infant position.

Conditions	Activities	
	Infant position	Caregiver action
No hold	On tummy	Caregiver is walking, standing or sitting
No hold	On back	Caregiver is walking, sitting or standing
Hold + moving	Vertical	Caregiver is comforting infant while walking, sitting or standing
Hold + moving	Horizontal	Caregiver is comforting infant while walking, sitting or standing
Hold + still	Vertical	Caregiver holds infant in either sitting or standing posture
Hold + still	Horizontal	Caregiver holds infant in either sitting or standing posture

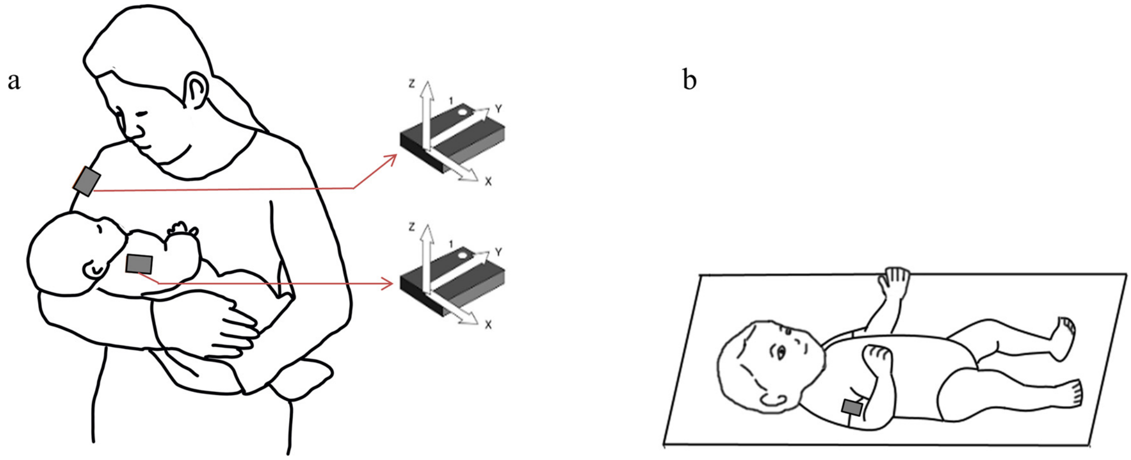

Fig. 1. (a) Schematic of the two-body sensor system. Each sensor was mounted on the infant's and the caregiver's upper arm and recorded 3-dimensional accelerations. The motion of the caregiver (moving vs. still) and the infant position (horizontal vs. vertical) was manipulated in different conditions. (b) During conditions of no physical contact, the infant was recorded on its own.

3.1. Qualitative analysis

Spontaneous movements in infants were measured in terms of infant active and inactive duration during different conditions. These behaviors were coded using the behavioral coding tool- Datavyu (www.datavyu.org). Since spontaneous movements are not observed when the infant is asleep, fussy or crying (Einspieler & Prechtl, 2005), video data was removed for durations in which these events occurred. Further, video data was discarded for the durations in which: (1) transition occurred between two conditions and (2) any video frame in which more than 50% of at least one limb of the infant was occluded. This procedure helped to ensure that infant active durations were coded only for conditions under investigation and that the coder had adequate visual information from the infant's limbs to accurately measure spontaneous activity.

Based on this data, we computed duration of infant active periods using the criteria: (1) movement seen in major parts of limbs (Lee, Ranganathan, & Newell, 2011) and (2) inactive period between two movements is no longer than 1 s (Piek & Carman, 1994; Thelen, 1981). In addition, physically restricted conditions were coded to see if caregivers restricted movement in the infant's right arm where sensor was placed. For example, physical restriction was counted if the infant was held in a way that their right side of the body was adjacent to the caregiver's body. In this case, infant's right arm movements where the sensor was placed can be restricted by caregiver's body. The duration of infant active behaviors and arm movement restriction by caregiver were coded independently by two coders- the primary coder coded 100% of all trials and the secondary coder coded 25% of all trials (Adolph et al., 2012; Franchak & Adolph, 2012).

3.2. Quantitative analysis

3.2.1. Identification of infant-caregiver physical contact

The first step in quantitative analysis was to identify the state of infant-caregiver physical contact in order to narrow down the portion of the data where infant generated activity estimation is needed. This included categorizing the activities into two main conditions: hold (caregiver holding infant) and no hold (caregiver is not holding infant). For this, a machine-learning based classifier was implemented to determine based 'only on the sensor data'. The rationale behind doing this (even though the experimenter had knowledge of the conditions) is that while we have video data in the lab setting, if the sensor system had to be used in a home environment (where potentially no video will be available), we should still be able to resolve periods of holding or no holding based on the sensor data. Thus the classifier allowed us to determine how well the sensor data could detect the conditions relative to the 'ground truth' known to the experimenters.

First, both caregiver acceleration data and infant acceleration data were split into 5-second samples. Then, from each sample, a histogram of caregiver acceleration data and a histogram of infant acceleration data were calculated. These 2 histograms were concatenated to form a feature for the respective 5-second sample. The rationale for using such a feature is that the 2 signals are expected to have more similar statistical characteristics when the caregiver is carrying the infant, and less similar characteristics when the infant is independent. Fig. 2 illustrates the sample features from data belonging to 2 conditions (hold and no hold). Finally, all the samples were evaluated using Random Forest classifier (Breiman, 2001) to determine their condition as – "hold" or "no hold".

The Random Forest (Breiman, 2001) classifier comprises of many tree-based classifiers (n = 200 in the described experiments). Each tree classifier is trained on a randomly selected subset of the attributes in the feature. Each member tree classifier stores its decision criteria in a tree data structure. The hold/ no hold status of a data sample can be predicted by traversing the tree in a top-down fashion, which is to start at the root node of the tree, evaluate the criterion on this node to determine which one of its child nodes is to be evaluated next, and repeat until there is no more child node to evaluate (i.e. reaches a leaf node). The output of the tree

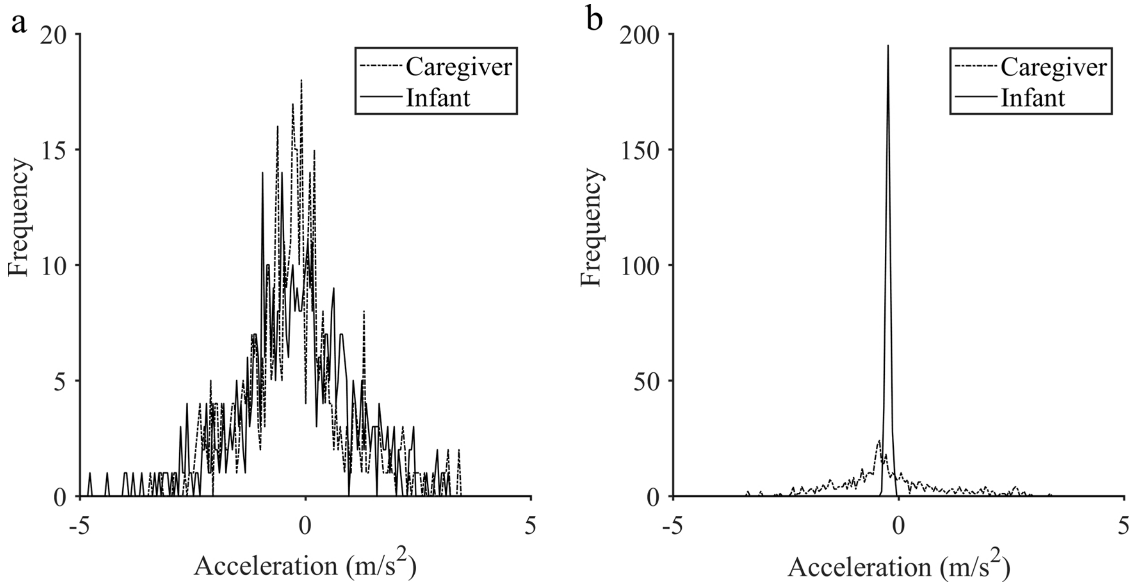

Fig. 2. Sample sensor signals from the caregiver and infant in the (a) Hold and (b) No hold conditions. In the Hold condition, the caregiver and infant signals show high similarity, as indicated by the histogram, whereas in the No Hold condition the caregiver and infant signals show distinct signatures.

is the condition label associated with that leaf. The final output of the forest is a popularity vote made from the outputs of all member trees. If more trees find the sample to resemble the "hold" condition than "no hold", the output will be "hold", and vice versa. On examining the classification results using this technique with the video data, an accuracy of 86.7% was obtained in categorizing the activities as hold and no hold conditions.

3.2.2. Estimation of Infant-generated activity

The next step in quantitative analysis was to estimate infant-generated activity. When the classifier detected a 'no hold' condition, the infant sensor data was directly used to estimate the infant-generated activity. When the classifier detected a 'hold' condition, we used an algorithm to remove the caregiver-generated movements from the infant sensor signals. The data processing for this algorithm (Fig. 3a) for estimating infant generated activity during physical interaction with caregiver was performed as follows:

First, the magnitude of acceleration from both caregiver and infant sensors (depicted as dotted lines in Fig. 3a) were extracted to yield the amount of movement regardless of the sensor orientation. Then, the infant sensor signal (S_{infant}) and caregiver sensor signal ($S_{caregiver}$) were fed as inputs to a Kalman filter (Fig. 3a) for estimating the amount of caregiver generated movements in infant signal. The Kalman filter (Kalman, 1960) is an algorithm to improve estimation of a value based on several noisy/inaccurate predictions and observations over time. A Kalman filter takes two signals, one is "prediction", and another is "observation". Usually, a prediction is an estimation of the value by extrapolation or indirect inference, while the observation is a measurement of said value by the sensor equipment. At each time point, the Kalman filter finds an optimal linear combination of those two signals to minimalize the observed channel noise. This tends to result in an estimation of the target value that has higher signal-to-noise ratio than either of the inputs. Based on the assumption that infant signals are a result of either their movement or movement produced by caregiver or a combination of both, the caregiver signal was used as prediction signal here.

Here we used a standard Kalman filter algorithm, where the Kalman gain was recalculated based on the last 10 samples. The standard Kalman filter (as opposed to an Extended Kalman Filter) was used for the following reason. The mechanical arrangement of the presented two-body system is modeled as one in which the caregiver sensor and the infant sensor are tied to one rigid body, which is the upper arm of the caregiver. It turned out that such a rigid body can be modeled as a linear system with a transfer function of a single constant gain factor. This linearity prompted us to use a standard Kalman Filter. Note that this single rigid body assumption holds when: 1) there is no significant movement in the lower arm of the caregiver, and 2) the infant does not move significantly. Meaning, the Kalman filter output is expected to be similar to the infant movement signal when the assumption holds. When the infant does move significantly, the output of the Kalman filter does differ, and we rely on this difference to detect the infant movements.

The Kalman filter outputs a weighted average between the prediction ($S_{caregiver}$) and the sensed infant signal (S_{infant}). It assigns less weight to S_{infant} whenever it showed poor correlation with the caregiver signal. The output of the filter (S_{output}) represents the infant signal with the infant generated movement suppressed.

$$S_{output} = f\,(S_{infant},\ S_{caregiver})$$

$$where,\ f = Kalman\,filter\,function$$

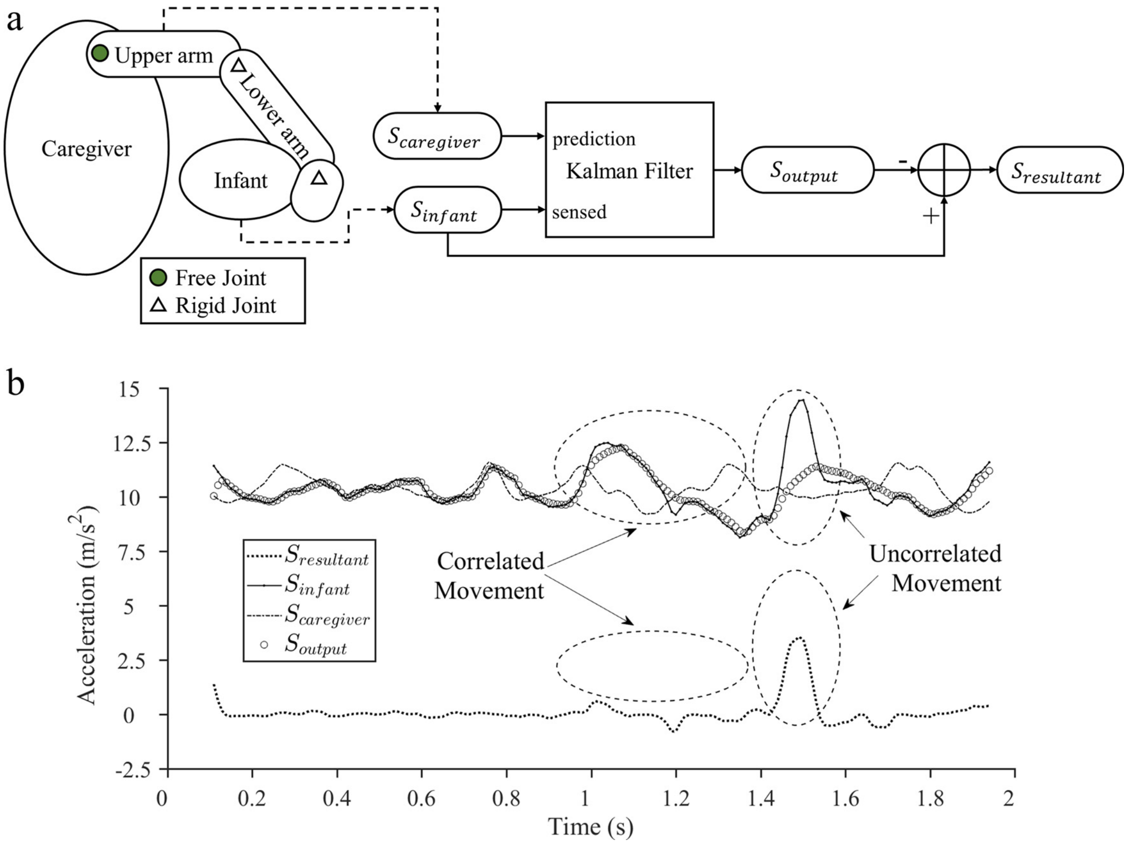

Fig. 3. (a) Schematic of sensor processing in the two-body system to identify infant-generated movement. Depending on the correlation between two signals, the Kalman filter produced a weighted average of the infant and caregiver signals, which allowed the identification of infant-generated movements, independent of the caregiver. (b) Sample data from infant and caregiver showing the extraction of infant-generated movement (called the 'resultant' here) using the Kalman filter. When the system detects correlated movement between infant and the caregiver, the system filters out the caregiver signal from the infant signal, resulting in much smaller resultant signal relative to the original infant signal. On the other hand, when the infant and caregiver signals are uncorrelated, the system recognizes the infant signal as being generated by the infant, which results in the resultant signal being roughly equal in magnitude to the original infant signal.

The difference between S_{infant} and S_{output} gave an estimate of the infant's signal ($S_{resultant}$) that is indicative of movements generated by them.

$$S_{resultant} = S_{infant} - S_{output}$$

It is important to note that this process does not naively subtract the infant and caregiver sensor signals directly; rather depending on the correlation between the signals, the algorithm extracts an estimate of the infant-independent movements from the two signals.

An example of the Kalman filter processing is shown in Fig. 3b. Consider the period between 1–1.4 s. The two input signals are highly correlated (which is characteristic of caregiver-generated movement), so S_{output} is not suppressed by the Kalman filter. As a result, $S_{resultant}$ is much smaller in magnitude compared to the original infant signal. On the other hand, the peak at 1.5 s on infant signal is poorly correlated with the caregiver signal (which is characteristic of infant generated movement). In this case, S_{output} is suppressed by the filter and $S_{resultant}$ shows a comparable magnitude to the original infant signal, indicating infant-generated movement.

3.2.3. Validation of algorithm using inanimate object

To validate how well the Kalman filter algorithm could extract infant-generated movements during physical contact, we collected data by attaching sensors on an inanimate object which acted as the 'infant'. This object was held and moved by a participant who acted as the caregiver. Since by definition, there is no 'infant-generated' movement in this case and all movements of the infant sensor are caused by the caregiver, the Kalman filter was expected to significantly reduce the power of the resultant signal. On comparing the inanimate "infant" signal power before and after the filtering, Kalman filter reduced the average power of the resultant signal by 92.2%, which indicates that the filtering scheme was effective in reducing caregiver-generated movements from the infant sensor signals. The existence of the residual signal is due to the uncertainties in the system, including but not limited to the imperfect time synchronization between the two sensors, the movement of the caregiver's lower arm/hand, and the fact that only one arm on

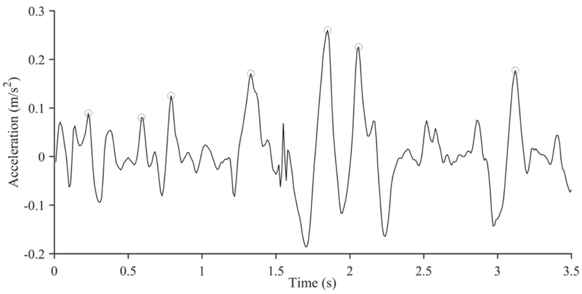

Fig. 4. Identification of acceleration peaks in one bout of infant active duration. A bout of infant active duration was defined as when there was movement seen in major parts of limbs and when the inactive period between two movements was no longer than 1 s. The number of acceleration peaks was divided by the time duration of the bout to estimate the number of peaks per unit time.

caregiver is equipped with the sensor while he/she can interact with the infant using both hands.

3.2.4. Kinematic analysis

The last step in quantitative analysis included kinematic analysis of the infant sensor data for the variables- acceleration peaks per unit time and dimensionless jerk. Kalman filtered infant sensor data was used for "hold conditions" while data from infant sensor was used directly for "no hold conditions". We used the number of peaks per unit time based on prior studies to account for differences in duration of activity (Bhat & Galloway, 2006). We also used the dimensionless jerk because it has been shown to be a more robust measure of movement smoothness as it relies on the entire signal, and is unaffected by changes in amplitude or duration (Lee & Newell, 2012; Rohrer et al., 2002).

The number of acceleration peaks was defined as the total number of local maxima that were greater than or equal to mean + 1SD in the acceleration profile of the movements during each condition (depicted in Fig. 4). As the total movement time was variable across different conditions and different participants, the number of acceleration peaks in each condition was measured per unit time.

For jerk analysis, dimensionless jerk was calculated as:

$$\sqrt{\int_0^{MT} \frac{J(t)^2}{2} dt * \left(\frac{MT}{a_{peak}^2}\right)}$$

where, J(t) is the derivative of the recorded acceleration, MT is the duration of total movement in a condition and a_{peak} is the peak acceleration during the condition. Typically, dimensionless jerk is calculated by normalizing jerk using the quantity (MT^3 / V_{mean}^2) (Hogan & Sternad, 2009), which makes the measurement of smoothness less biased with changes in the overall movement time (Lee & Newell, 2012; Rohrer et al., 2002). Since our raw data was instantaneous acceleration, we used a modified dimensionless jerk in which jerk was normalized by a quantity (MT/a_{peak}^2).

4. Statistical analysis

Descriptive data are shown for all 15 sessions of data collection as this data was used for training the classifier. However, for statistical analysis only data from seven sessions (one session per participant) out of 15 were included since some participants were tested multiple times. When a participant was tested multiple times, the selection of the dataset for statistical analysis was based on the age of participant at the time of lab visit; the session that most closely matched the age of other participants was used for analysis.

To examine the overall effect of physical contact (regardless of infant position), a one-way repeated measure ANOVA was performed to measure the effect of physical contact (hold + moving, hold + still, no hold) on active duration of infant, acceleration peaks per unit time and dimensionless jerk. This one-way ANOVA was run separately because our experimental conditions were not fully crossed (i.e., infant position was not the same for the hold conditions as it was the for the no hold conditions).

To separate the effects of infant position during physical contact, a two-way 2 × 2 repeated measure ANOVA was performed to measure the effect of physical contact and infant position on active duration, acceleration peaks per unit time and dimensionless jerk. The factors were physical contact (hold + moving, hold + still) and infant positions (vertical, horizontal). Post hoc comparisons were made using Tukey's post hoc test with the significance level set at $p < 0.05$. Violations of sphericity were corrected using the Greenhouse-Geisser correction when appropriate.

5. Results

5.1. Descriptive measures

No infants were excluded from data analysis, but video and sensor data were discarded for both qualitative and quantitative analysis for all durations during which 1) infants showed fussiness or cried, 2) caregivers transitioned between two conditions, and 3) infant limbs were not adequately visible. Out of 40 min of each dataset, percentage duration during which infants cried showed large

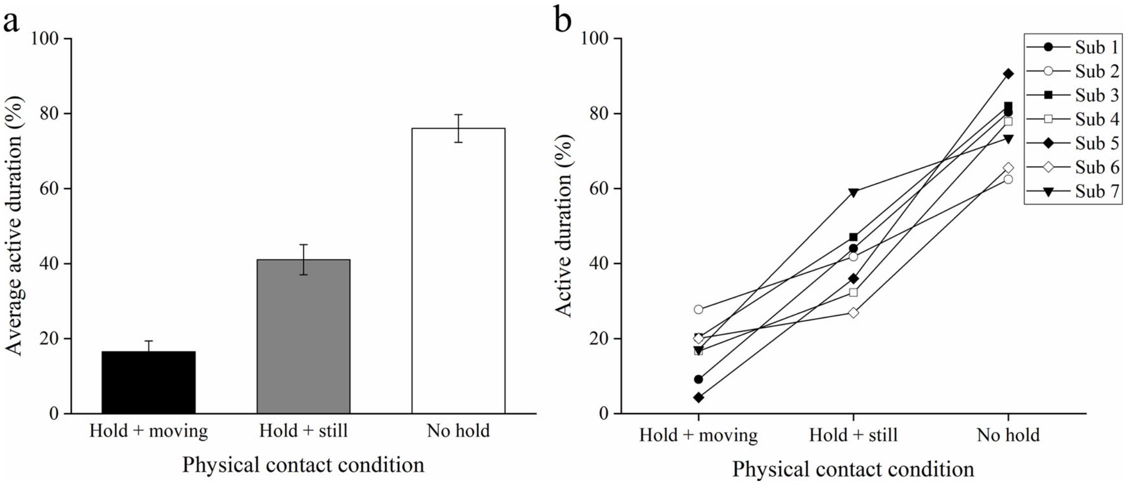

Fig. 5. Effect of physical contact condition on infant active duration. (a) Average active duration (%) across all 15 sessions with 7 infants (some infants were tested multiple times). Error bars represent one standard error (between-participant). (b) Active duration for each of the 7 infants as a function of physical contact. Higher active duration was observed when there was no physical contact between the caregiver and the infant.

variation (*Mean* = 14.78%*; range* = 0.90–49.36%). However, the percentage duration in which either caregiver was transitioning between the conditions (*Mean* = 11.69%; range = 8.85–16.45%) or infant limbs were not adequately visible on video (*Mean* = 9.75%; *range* = 4.95–16.25%) was fairly consistent across 15 datasets. A fairly high percentage of video and sensor data (*Mean* = 78.72%; *range* = 71.68–85.24%) was available even after discarding for the before mentioned durations for further qualitative and quantitative analysis. For quantitative analysis, the infant sensor data that was incorrectly classified as "hold" or "no hold" conditions by the Random Forest classifier was discarded from further analysis (*Mean* = 5.62%; *range* = 2.43–10.01%)

5.2. Infant active duration

The inter-rater reliability between the two coders for coding frequency and duration of infant behaviors (active and inactive) based on the video data was generally high (the Kappa agreement for frequency of infant behavior was 0.96; average percentage agreement on duration of infant behavior was 93%).

The percentage of average active duration as a function of physical contact across 15 datasets showed that infants were more active during no hold condition and least active during hold + moving condition (depicted in Fig. 5a). A one-way repeated measure ANOVA on 7 datasets confirmed that there was a significant main effect of physical contact, $F(2, 12) = 59.4$, $p < .001$ on infant active duration. Post hoc comparisons showed that the percentage of infant active duration in no hold condition was significantly higher than in the hold + moving and hold + still conditions.

Further, the effect of caregiver movement during physical contact (hold + moving, hold + still) and infant positions (horizontal, vertical) was assessed on infant active duration. The average infant active duration (%) across 15 datasets indicated more activity during hold + still condition as compared to hold + moving and less activity during vertical position as compared to horizontal for each of the physical contact conditions (Fig. 6a). Active duration from 7 infants analyzed using 2 × 2 ANOVA showed a significant main effect of caregiver movement, $F(1, 6) = 8.34$, $p = 0.028$, a significant main effect of infant position, $F(1, 6) = 12.46$, $p = 0.012$, but no statistically significant effect of interaction between them, $F(1, 6) = 0.81$, $p = 0.404$.

5.3. Infant arm restriction

While the qualitative analysis of infant active duration involved movement in any of the four limbs, quantitative analysis was more representative of the infant right arm kinematics due to sensor placement on right arm. Thus, one potential confound in analyzing kinematics for the hold vs. no hold conditions is that the holding style of the caregiver may have restricted movement of the infant on the side where the sensor was placed (for example, if the infant sensor was on the right arm, the caregiver may have held the right side of the body adjacent to his/her body). To rule out this potential confound, we did a further analysis on whether the infants' arm was restricted during the data collection. The inter-rater reliability between the two coders for coding frequency of infant right arm restriction by caregiver during physical contact conditions was high (the Kappa agreement was 1). Percentage duration in which caregiver restricted infant's right arm movement ranged from 0–to 46.43% (*mean* = 10.56%; *SE* = 3.84). The holding style of caregivers led to no infant arm restriction in six datasets, moderate arm restriction in 5 datasets (*range* = 3.25–13.18%) and large amount of arm restriction in 4 data sets (*range* = 23.09–46.43%). We further reviewed video data of datasets with moderate to large amount of arm restriction to rule out if restriction of other limbs was a potential confound for qualitative data analysis. Despite moderate to large amount of arm restriction in 9 out of 15 datasets, their video data review indicated that at least 2 of the infant limbs were unrestricted at any given time. Thus, the holding style of caregiver may have affected the kinematic findings for few datasets but

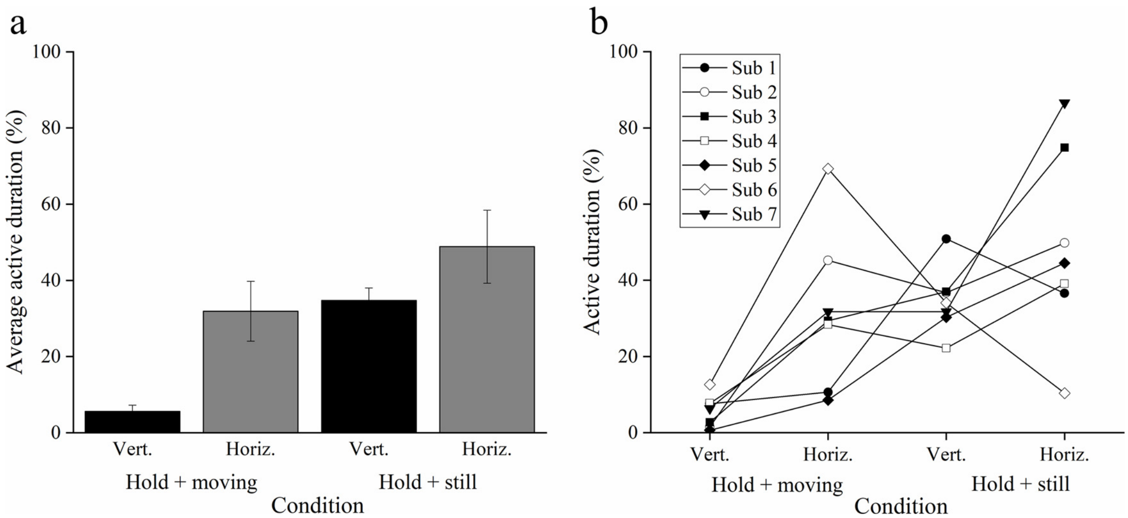

Fig. 6. Effect of caregiver motion and infant position during physical contact on active duration. (a) Average active duration (%) across 15 sessions with 7 infants (some infants were tested multiple times). Error bars represent one standard error (between-participant). (b) Active duration for each of the 7 infants used for statistical analysis. Higher active duration was observed when the caregiver was still, and when the infant was horizontal.

it was not the primary factor influencing qualitative findings on infant active-inactive behavior during physical contact conditions.

5.4. Acceleration peaks per unit time

Acceleration peaks per unit time across 15 datasets as a function of physical contact showed more number of peaks in the no hold condition with least number of peaks in the hold + still condition. In order to measure this effect, acceleration peaks per unit time was analyzed using one-way repeated measure ANOVA with a within-subject factor of physical contact (hold + moving, hold + still, no hold). There was no statistically significant main effect of physical contact on acceleration peaks per unit time ($F(1.18, 7.05) = 1.87$, $p = 0.217$) (Fig. 7a).

A 2 × 2 repeated measure ANOVA with two within-subject factors of physical contact (hold + moving, hold + still) and infant position (horizontal, vertical) also showed no statistically significant main effects of physical contact ($F(1, 6) = 2.0$, $p = 0.207$), infant position ($F(1, 6) = 2.40$, $p = 0.172$) as well as their interaction ($F(1, 6) = 3.47$, $p = 0.112$) (Fig. 7b).

5.5. Dimensionless jerk

As a function of physical contact (hold + moving, hold + still, no hold), average dimensionless jerk across 15 datasets was highest ($J = 349.28$) for no hold conditions and lowest ($J = 155.85$) for hold + moving condition. A one-way repeated measure ANOVA on 7 datasets confirmed that there was a significant main effect of physical contact, $F(2, 12) = 7.34$, $p = 0.008$ on dimensionless jerk (Fig. 7c). Post hoc comparisons showed that the dimensionless jerk in hold + moving and hold + still conditions was significantly lower than in the no hold conditions. A two-way repeated measure ANOVA with two within-subject factors of physical contact (hold + moving, hold + still) and infant position (horizontal, vertical) showed no statistically significant main effects of physical contact ($F(1, 6) = 1.396$, $p = 0.282$), infant position ($F(1, 6) = 3.413$, $p = 0.114$) as well as their interaction ($F(1, 6) = 0.046$, $p = 0.837$) (Fig. 7d).

6. Discussion

The aim of this study was to examine the role of physical contact and infant position on the characteristics of spontaneous movements in infants. A novel contribution was the development and validation of a ‘two-body’ sensor system that identifies periods of physical interaction with infants and estimates their activity independent of caregiver movements with high accuracy (92%) using machine learning techniques. Using behavioral coding and kinematic analyses, we found that both physical contact and infant position modulated the characteristics of spontaneous movements. To our knowledge, this is the first study of its kind to perform kinematic analysis on infant-generated spontaneous movements while they were in physical contact with a caregiver.

In terms of the role of physical contact on spontaneous movements, both behavioral and kinematic analyses showed a similar trend that infants were more active during no hold condition. A simple explanation of this effect could be that infant movements were physically restricted which caused less spontaneous activity. However, we ruled out this possibility by looking at how caregiver was handling the infants and confirming that the caregiver did not physically restrict the movements of the infants in a majority of the settings. Our finding that infants were more active during no hold condition is consistent with Thelen’s description (Thelen, 1981) that despite individual differences between infants, the amount of the spontaneous movements were highly correlated with the time

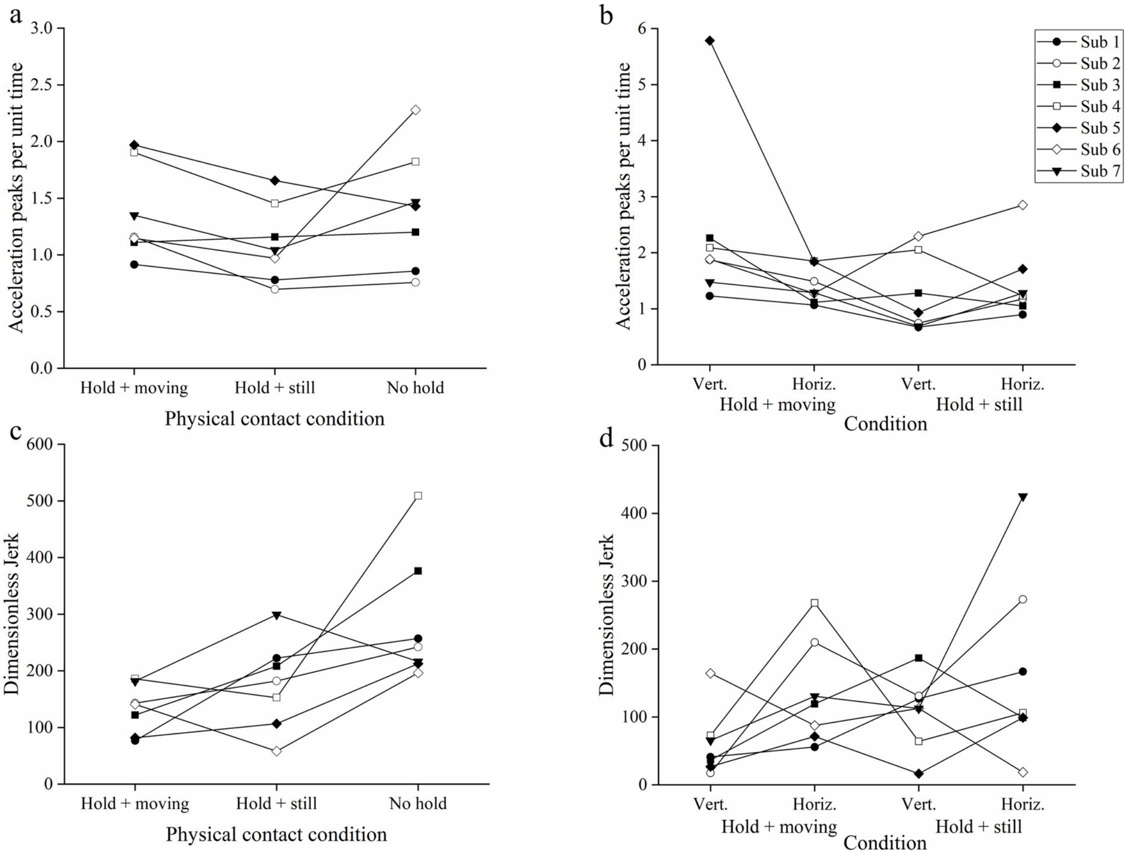

Fig. 7. Acceleration peaks per unit time across 7 infants used for statistical analysis as a function of (a) physical contact conditions (b) caregiver motion and infant position during physical contact. There were no clear differences in the observed number of acceleration peaks per unit time across conditions. Dimensionless jerk across 7 datasets used for statistical analysis as a function of (c) physical contact conditions (d) caregiver motion and infant position during physical contact. Dimensionless jerk was higher in the no hold condition but there were no clear effects of caregiver motion or infant position.

spent in contact with caregiver. Although our study was not designed to test the mechanistic reasons behind why this phenomenon occurs, two related explanations can account for this finding. The first is that the function of the spontaneous movements is to serve as 'compensatory' self-stimulatory movements (Thelen, 1981). Therefore, when the infant is held by the caregiver, there is less need for self-stimulation, resulting in a decrease in the amount of spontaneous movements. The second explanation is the presence of a general 'calming response' that is observed when infants are in the presence of caregivers (Esposito, Setoh, Yoshida, & Kuroda, 2015), which may account for the differences between the no hold and the hold conditions.

In addition to the duration of activity, our kinematic analyses also indicated with physical contact resulting in smoother movements (i.e. smaller jerk) relative to no physical contact. Prior research has shown that spontaneous movements generally become smoother prior to onset of goal directed activity (Bhat & Galloway, 2006; Lee et al., 2011), and this has been taken as evidence to support the claim that spontaneous movements are not 'random' movements that disappear suddenly in development, but are actually sculpted into more coordinated goal-directed movements (Turvey & Fitzpatrick, 1993). Although future studies are needed to address the significance of this change in smoothness in the current context of physical contact, these results suggest that physical contact not only affects the amount of spontaneous movements, but also the quality of movements observed.

In terms of the role of infant position during physical contact with the caregiver, behavioral analyses showed less infant movements when the caregiver was actively moving the infant and when the infant was held in the vertical position. This effect of caregiver movements while holding the infant supports previous studies, in which less infant movements were attributed to reduction in heart rate when they were simultaneously held and moved (Esposito et al., 2013, 2015; Gammie, 2013). For the infant position effect, our findings seem contradictory to previous studies in which increased arm movements were seen in vertical position of infants as compared to supine position (Carvalho et al., 2007; Lobo & Galloway, 2008; Savelsbergh & van der Kamp, 1994; Soska & Adolph, 2014; Spencer, Vereijken, Diedrich, & Thelen, 2000; van der Fits, Klip, van Eykern, & Hadders-Algra, 1999). However, a critical difference is that in prior studies, the effect of infant position was assessed during periods of no physical contact, whereas in our study, it was assessed during physical contact with the caregiver. Given that spontaneous movements are sensitive to individual and environmental factors, it is likely that physical contact may be an environmental 'constraint' that potentially alters the observed behavior relative to when there is no physical contact (Newell, 1986).

A key contribution from the current study is the development of a novel two-body sensor system that accurately identifies when the infant is being held, as well as estimates their active movements during these intervals. Traditional methods of data collection such as video recording provide rich contextual information such as the presence and type of physical contact but have problems for long-term recordings including privacy concerns, data loss due to obstruction of the camera, and the need for time consuming frame-by-frame analysis (Haidet, Tate, Divirgilio-Thomas, Kolanowski, & Happ, 2009; Latvala, Vuokila-Oikkonen, & Janhonen, 2000). Alternatives such as commercially available wearable accelerometers (e.g. Actigraph) have the potential for making longer recordings with automated analyses but critically, they cannot separate infant-generated movements from passive movements generated by caregivers or mechanical devices like bouncers (Pitchford, Ketcheson, Kwon, & Ulrich, 2017). However, our two-body sensor system can identify the periods of physical interaction between infants and caregiver for long hours. Specifically, the Kalman-filter technique used for signal separation of infant movements from caregiver generated movements is a robust method to handle issues such as phase shift, magnitude mismatch and other irregularities in the sensor signals (Xie & Soh, 1994). As a result, this may open new opportunities to characterize infants' spontaneous movements in a naturalistic setting even in the presence of physical and mechanical influences.

Beyond the measurement of spontaneous movements, the two-body sensor system developed here has potential broader applications for measurement of infant activity in general. This system can not only reduce the reliance on traditional methods (such as parental logs) which can be burdensome, but can also provide fine-grained information regarding this activity (e.g., assessing the total duration caregivers spent in holding their newborn infants, or that infants spent in mechanical devices such as bouncers). Similarly, while we used only acceleration magnitude here (which eliminated any effect of acceleration direction), examining the acceleration in specific directions with a more careful placement of sensors could yield information about infant positioning (e.g., supine lying or reclined sitting) that could also be used to quantify the time spent in different positions. Ultimately, we believe that accurately estimating infant motor behavior using these sensors in a home environment has important implications for understanding both typical and atypical development.

The current study findings have to be considered in the context of a few limitations. First, the sample size was relatively small and we were not able to conduct repeated evaluations of all the included infants. Future work should be designed to conduct longitudinal evaluation in a larger sample size. Second, we used only a single sensor on the infant arm and the caregiver to demonstrate initial proof of concept. This limited the motions that we captured using the sensors and is potentially responsible for some discrepancies between the video coding analyses (where all movements were captured) and the kinematic analyses from the sensors. Moreover, because we attempted to mimic a natural situation, we used a variety of different infant and caregiver interactions that all constrained motions somewhat differently (e.g., the tummy position had greater restrictions on arm motion, the caregiver could use different degrees of rocking, bouncing motions etc.). The use of more sensors in future studies could lead to a greater movement repertoire being captured; however, this has to be balanced against the greater complexity introduced by a larger number of sensors – both from feasibility and measurement standpoints. Finally, because our Kalman Filter algorithm does not completely suppress caregiver movement (i.e. some 'infant-generated' movements were observed even in the case of the inanimate object), some of the quantitative comparisons between hold and no-hold conditions could be affected by artifacts due to this imperfect filtering. Future studies using more comprehensive validation techniques (e.g., using a robotic device to mimic spontaneous movements) could provide more insight into estimating and improving the accuracy of filtering.

In summary, the findings of this study add to existing literature on the importance of physical interaction during infancy by indicating that its effects extend to infant motor development. The ability to record spontaneous movements during physical contact over long-time periods is especially relevant for early detection of conditions such as autism spectrum disorder (ASD), where infants find difficulties with cooperative adjustment of their body to caregiver holding (Esposito et al., 2013; Kanner, 1968). Understanding the dynamics of these physical interactions may provide an important window to investigate infant motor development in home-based experimental studies.

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